ATMOSPHERIC STUDIES AND APPLICATIONS WITH INFRARED HETERODYNE DETECTION TECHNIQUES

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ABSTRACT

With the advent of stable, cw infrared lasers with moderate output power capabilities in the mid 1960's came the idea of using heterodyne detection, a mature radio frequency technique, in the infrared. This technique was first applied in radar and communications applications; however, a few years later it became apparent that infrared lasers and heterodyne detection techniques would be useful in a number of atmospheric measurement applications. The objective in this paper is not to attempt a survey of atmospheric measurement applications, many of which are represented by papers in this conference proceedings, but to indicate the level to which these techniques are being put to use in field measurements, using two developed flight instruments as examples.

INTRODUCTION

Heterodyne detection techniques are important in a variety of atmospheric measurement applications, because of the improvement in overall sensitivity which can be achieved when using high spectral resolution infrared measurements to probe the atmosphere. An infrared spectrum of the atmosphere contains a wealth of information about its chemical composition, and a careful study of the "window" regions (e.g., 3-4 μm, 8-14 μm) with a high resolution instrument will result in quantitative information about a large number of important trace constituents. The high spectral resolution usually enhances sensitivity and minimizes overlap or interference effects with other molecules. Heterodyne detection in the infrared depends on the availability of suitable lasers which can be used as local oscillators, transmitters, or both. Laser transmitters which emit at various frequencies in the "window" regions are particularly desirable, for one can use these devices to probe atmospheric regions without having to depend on sunlight or on the thermal emission properties of the species. Heterodyne radiometers which observe thermal radiation spectra are more useful at the longer wavelength "window" region, because the brightness of emitters at atmospheric temperatures peaks in this region and falls off rapidly at shorter wavelengths. Consequently, lasers which can be used as local oscillators in this wavelength region have special appeal. The grating tunable CO_2 lasers have been used for this purpose in several atmospheric measurement applications (Refs. 1-4), including studies of other planetary atmospheres which are

discussed in this Conference. The lead salt diode lasers are now being used more frequently in various measurements, and their use will certainly expand along with improvements in device technology.

In this paper, certain representative examples of atmospheric measurements with instruments employing heterodyne detection will be discussed. The examples chosen are flight instruments which have been used in several field measurements, and are indications of the potential for use of laser heterodyne technology in applications requiring ruggedized design. Several other papers in this session of the HST Conference will address recent ground-based measurements with other systems, and plans for future earth-orbiting laser heterodyne radiometers.

OZONE MEASUREMENTS WITH A LASER ABSORPTION SPECTROMETER

An airborne instrument which employs a downward-pointing laser transmitter and a matching heterodyne receiver can be used to measure pollutant concentrations in the vertical path between the instrument and ground, with modest transmitter power requirements. With a 1 watt laser and a 5 cm collecting aperture, the instrument can detect the small fraction of transmitted laser radiation which scatters off the ground and is collected at the aperture, with high enough signal-to-noise ratio to make a measurement in a few seconds integration time, at altitudes as high as 15 km. This type of instrument, measuring differential absorption at preselected wavelengths, has a high sensitivity to trace constituents at any altitude in the troposphere, whereas passive radiometric sensors are often ineffective in this application because the low altitude pollutants are at nearly the same temperature as the earth's surface.

Tropospheric ozone measurements have been made using an active, nadir-looking laser absorption spectrometer (LAS) in NASA aircraft over the past three years (Ref. 5). The LAS employs two discretely tunable CO_2 waveguide lasers and two heterodyne receivers, each tuned to detect signal returns from one of the two transmitted frequencies. A single telescope, with a 15 cm diameter primary mirror, is divided into four non-overlapping sub-apertures, two for the transmitted wavelengths and two for the independent heterodyne receivers. The application of the LAS to the mapping of ozone distributions over an urban area is shown pictorially in Figure 1. The LAS optical head, with one side cover panel removed, is shown in Figure 2. This illustrates the compactness which can be achieved with the use of waveguide lasers. In flight operation, one laser has been tuned to either the P(22) or P(24) line, which occur at frequencies where ozone absorbs very little, and the other laser has been tuned to either the P(12) or P(14) lines. Absorption coefficient data such as that shown in Figure 3 are used to calculate ozone column abundances from differential absorption measurements.

The first series of LAS flights, in the Beechcraft Queen Air February 28 through March 2, 1977, demonstrated that the measurement concept was sound. Using an integration time of a few seconds, the received signals showed very little noise. The high dynamic range capability of the receivers was sufficient

to handle large albedo fluctuations and speckle fluctuations and effectively time average them as we had hoped. The albedo fluctuations with large spatial scale (periodicities longer than 10 seconds) were present on both receiver channels and were well correlated with each other. Figure 4 is a portion of the strip chart recording taken February 28, indicating a passage from coastal land to water near Ventura, California, at a 2.5 km altitude. The high correlation between channels, as the aircraft passed over a variety of terrain, is evident. As a result, the ratio of the two receiver signals was a viable indication of differential absorption due to the atmosphere. There is very little interference from other tropospheric species at these wavelengths. However, measurements taken during recent flights over various parts of the continental U.S. indicate the possibility of interference from spectral albedo features of certain types of terrain. This effect is noticeable during low altitude flights (e.g., 800-1000 meters altitude), when it becomes necessary to measure differential absorption to a 2-3% accuracy level in order to accurately measure background tropospheric concentrations.

Recently the LAS was flown in the Southeastern Virginia area, along with a Cessna 402 which was instrumented with in-situ ozone measurement instruments, in a correlative ozone measurement program. The Cessna operation was directed by NASA Langley Research Center personnel. Data taken during Cessna spirals were compared with ozone column abundance data from the LAS. An example of these data is pictured in Figure 5. In this case, the LAS flew repeatedly over a location near Cape Charles, at three altitudes, and the results were compared with vertical spiral data. These results indicate the agreement which can be obtained when flying over water, or terrain for which spectral albedo features are either absent or previously calibrated. Various means for reducing LAS susceptibility to terrain spectral albedo are under investigation.

PASSIVE HETERODYNE RADIOMETRY

The wavelength dependence of heterodyne radiometer sensitivity to thermal radiation is shown in Figure 6. It is apparent that the sun is a good source for high spectral resolution atmospheric transmission measurements. The factor plotted in Figure 6 is multiplied by the radiometer factor, $(B_{IF}\tau)^{1/2}$ and various quantum and optical efficiency factors to obtain the signal-to-noise ratio, where B_{IF} is the receiver IF bandwidth and τ is the integration time. When the atmosphere is transparent at a frequency corresponding to a wavelength near 10 micrometers, the S/N ratio for a 20 MHz bandwidth and a 10 second integration time is about 6000. In practice, optical losses, instabilities of the solar image on the photodetector, and atmospheric effects degrade this S/N by several dB; however, there remains sufficient S/N to conduct measurements of trace species with high accuracy.

In order to remotely measure trace constituents in the stratosphere, a technique with very high sensitivity involves putting a solar heterodyne radiometer on a high altitude platform, e.g., a balloon gondola, and measuring the solar absorption spectrum from stratospheric altitudes, near sunrise or sunset. The solar occultation geometry is pictured in Figure 7. From a location in the upper stratosphere, an instrument which views the sun at a zenith angle of

slightly greater than 90° can interact over a total path length of 500 km with a portion of the stratosphere whose vertical extent is 3 km. Typical geometric weighting functions associated with this type of measurement are given in Figure 8. The high sensitivity, high vertical resolution capability, and freedom from attenuation or interference due to tropospheric or lower stratospheric species (e.g., ozone) makes this type of measurement attractive. A balloon-borne laser heterodyne radiometer (LHR) was developed at JPL for stratospheric flights beginning March, 1978, and extending through the present, in order to measure reactive trace species. Man-made halocarbons have been postulated as potentially dangerous sources of chlorine in the stratosphere (Refs. 6, 7); however, measurement data for several key species in the ozone destruction reactions, such as chlorine monoxide, are scarce. In Figure 9 are presented chlorine monoxide profiles observed during two separate LHR measurements, along with a current photochemical model prediction. (The launch location for the two balloon-borne measurements was Palestine, Texas.) Measurements indicate peak mixing ratios which are slightly higher than model predictions indicate. These data are not inconsistent with data from several in-situ measurements of chlorine monoxide by Anderson and colleagues (Ref. 8). Further measurements of chlorine monoxide, along with simultaneous measurements of other reactive stratospheric species, are planned for the near future.

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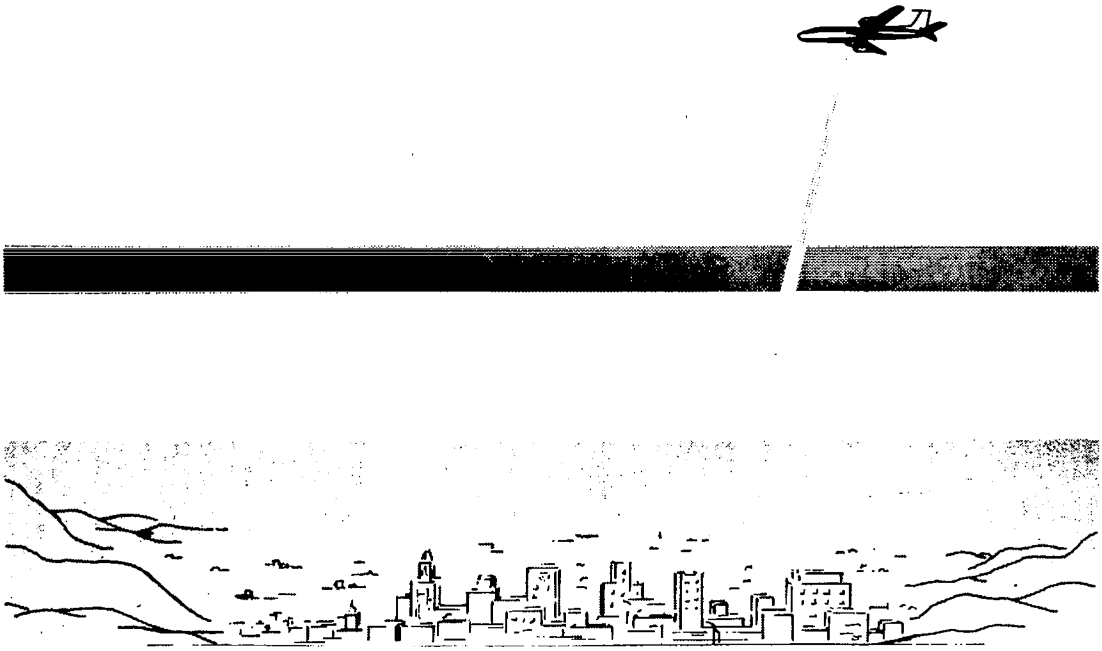

Figure 1.- The Laser Absorption Spectrometer, mounted in an aircraft, can map the distribution of ozone and other selected species in an urban area.

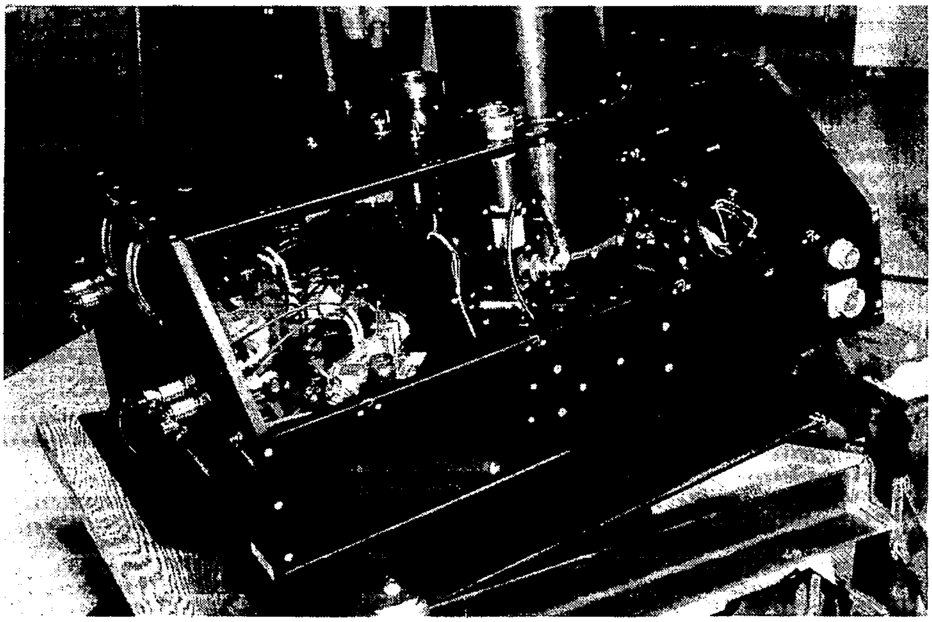

Figure 2.- LAS optical head with one panel removed. One waveguide laser, with its white BeO section visible, can be seen in the foreground near the left end. Photodetectors are mounted in liquid nitrogen dewars clamped to the telescope tube.

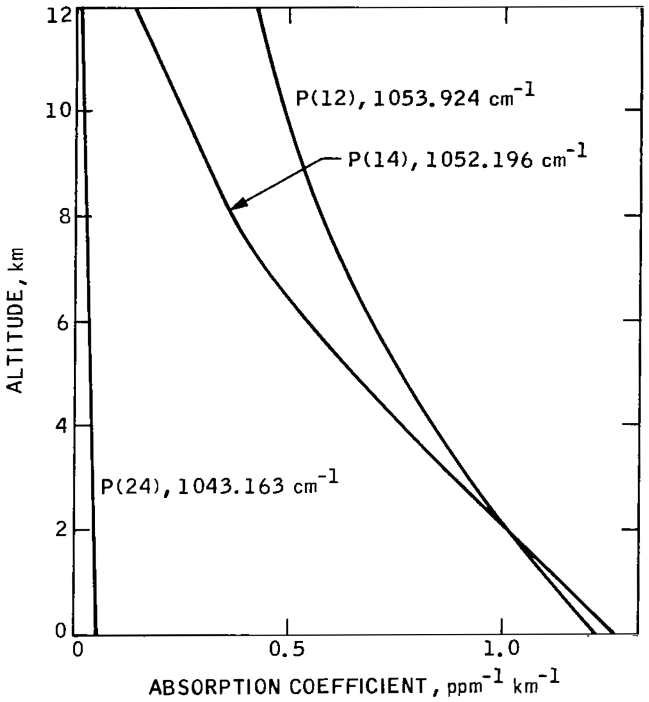

Figure 3.- Tropospheric ozone absorption at selected CO_2 laser frequencies.

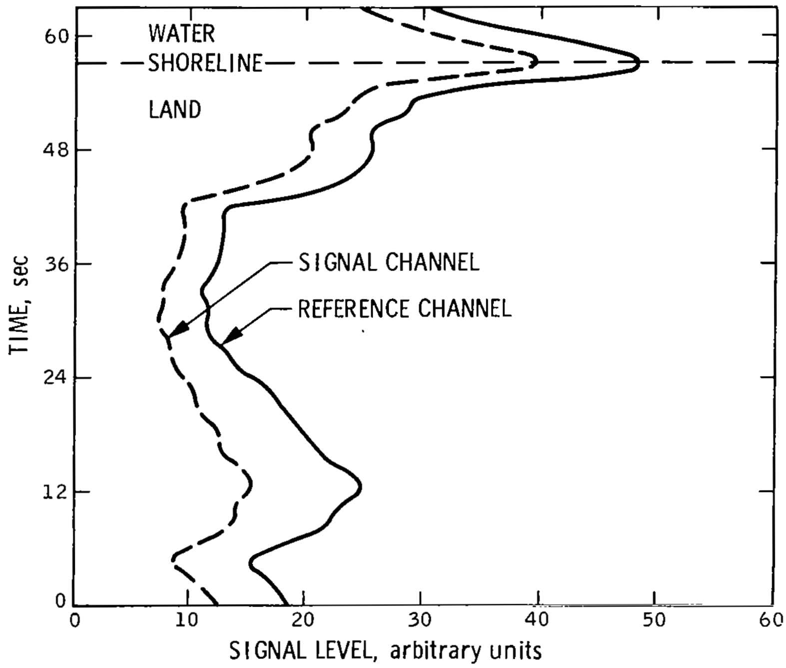

Figure 4.- Reproduction of a portion of the LAS strip chart recording, showing the high degree of correlation between the signals at the two receiver channels.

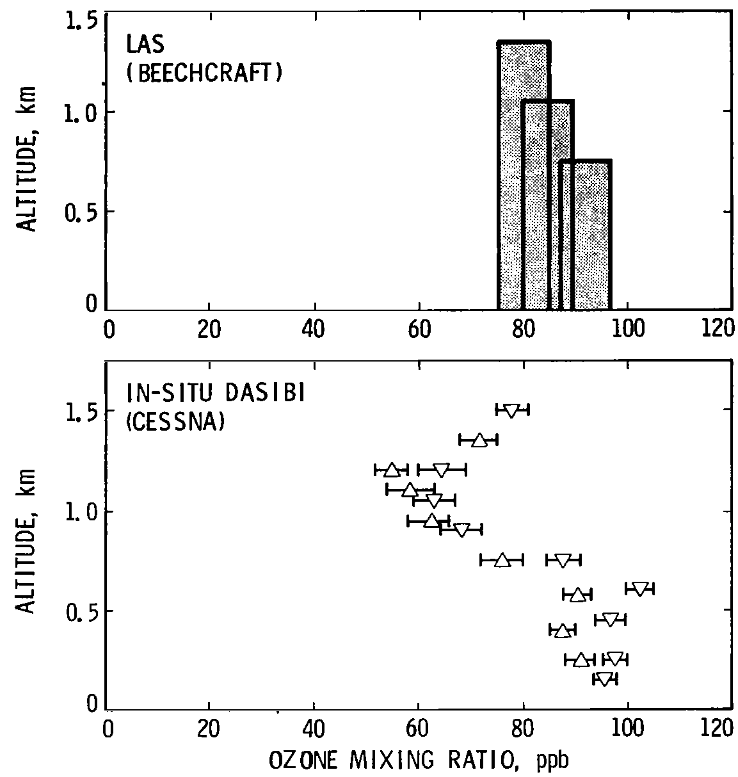

Figure 5.- Ozone measurements over Cape Charles, Virginia, 9 August 1979.

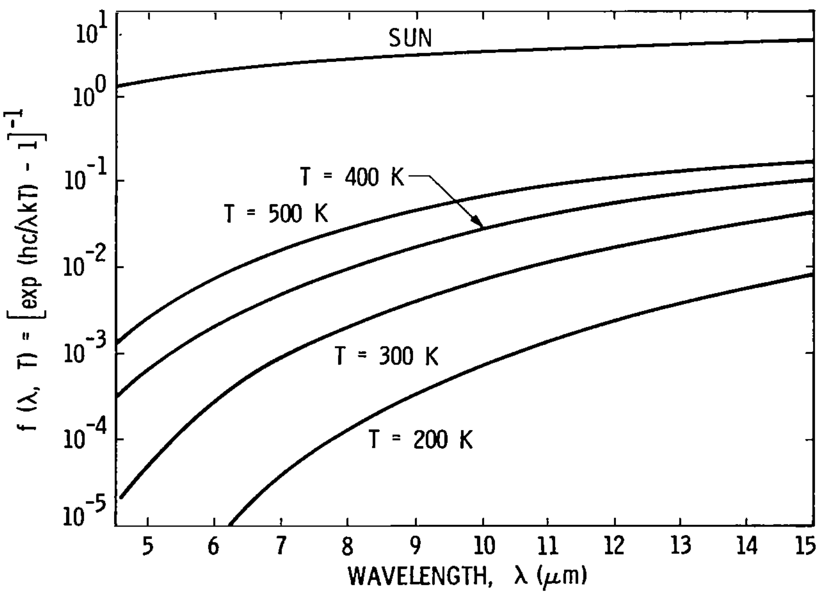

Figure 6.- Heterodyne radiometer sensitivity to thermal radiation.

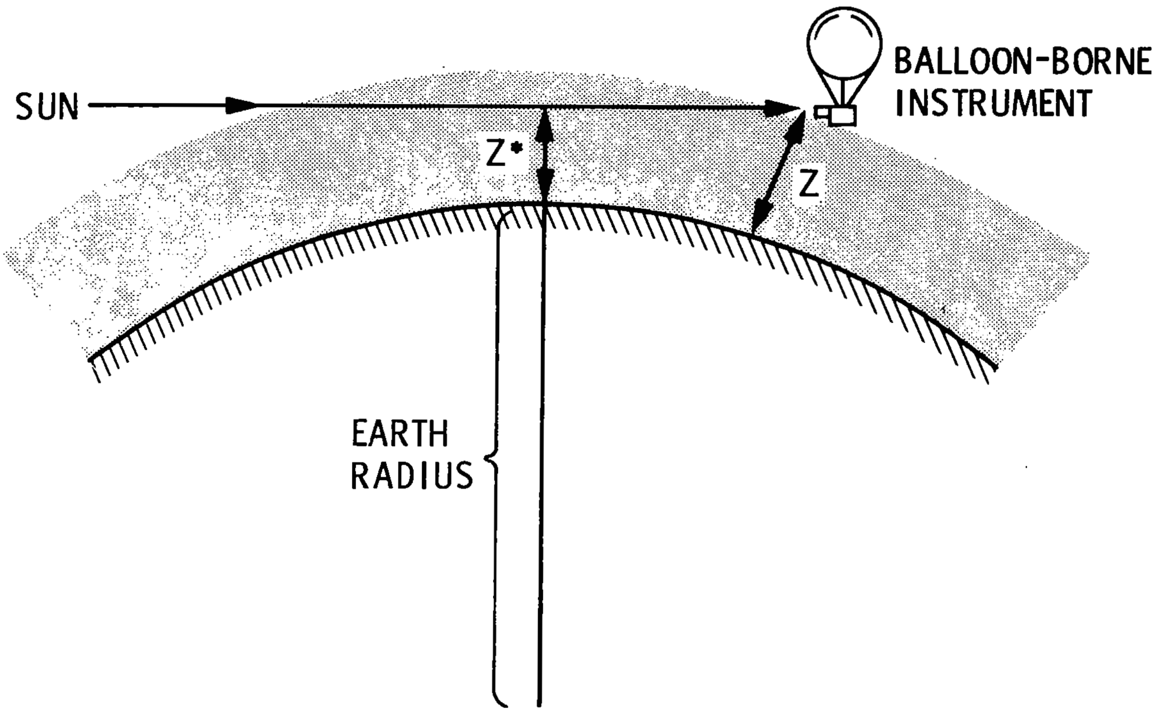

Figure 7.- Solar occultation geometry using a balloon-borne instrument.

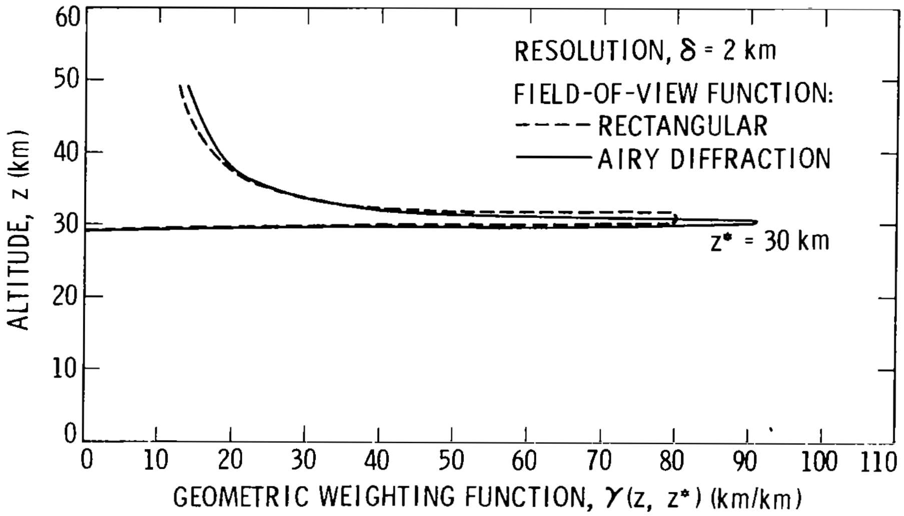

Figure 8.- Limb sensing geometric weighting functions.

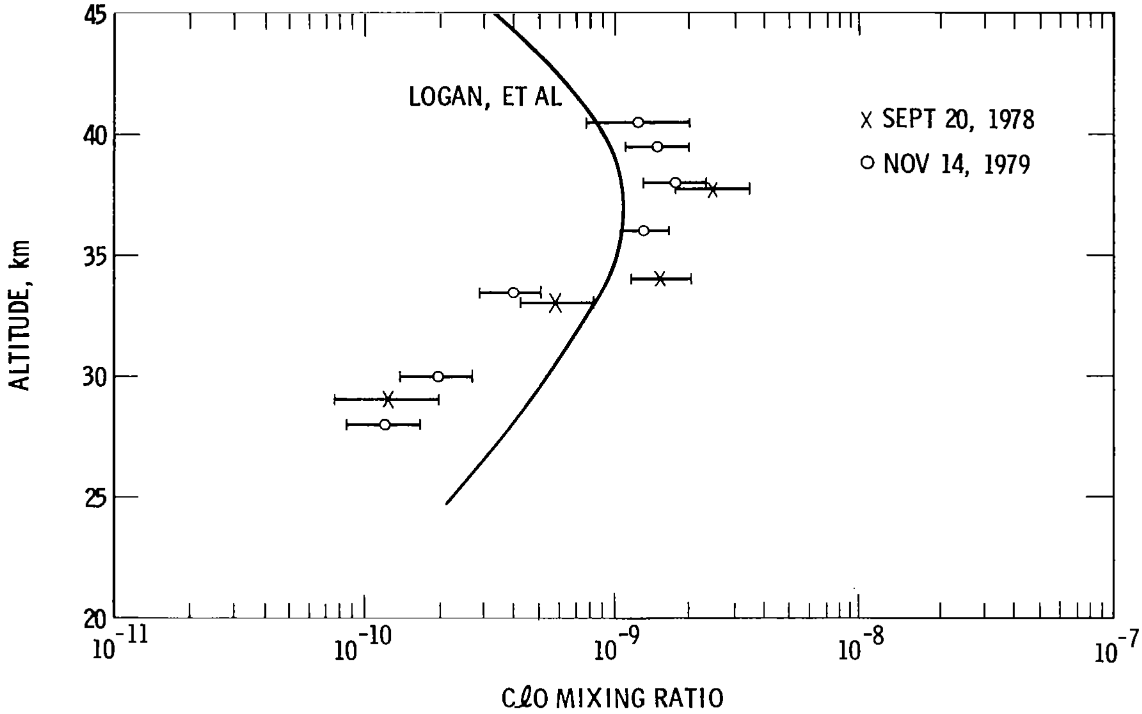

Figure 9.- LHR measurements of chlorine monoxide profiles.